

Note that the times shown in the study plan overleaf do not include the time that you will need to answer questions on the DVD and the TMA, making use of the set book, attending sessions at your local or regional centre or reflecting on what you have learned and how you have learned it. Past students have also commented that *our* estimates of the times needed for the study of the DVD-multimedia activities are likely to be low.

Study Guide for Block 11

This block marks the final destination in our quest of 'putting the world back together'. *Universal processes* refer to the physical interactions that occur throughout the time and space of the Universe. In Block 11 therefore, you will be learning about the very origin of the Universe itself, about the ultimate constituents from which it is built, and about the fundamental interactions that govern all processes occurring within it. *There is no bigger subject than this*. The topics discussed here underpin all other areas of science, and many of them are currently at the forefront of scientific research. For this reason, some of the ideas discussed here are a little speculative. This serves to illustrate that many areas of science are not cut-and-dried subjects, but are ever-developing fields with new ideas continually arising and subsequently being accepted or discarded.

Block 11 builds on the information about quantum physics and fundamental particles that you learnt about in Block 7. It also deals with very large and very small scales of distance, time and energy, which requires you to be comfortable with manipulating powers of ten. Several of the activities in Block 11 allow you to revise this material, in order to prepare for the developments of it that you will meet here. For reference, a summary of particles is given overleaf.

The book contains most of the material that you will need to study the block, but there are a number of other activities also. Embedded within Section 2 is a DVD-multimedia activity entitled 'The virtual telescope'. Using your computer you will take measurements of galaxies from which you will be able to measure the expansion rate of the Universe and so calculate its age. The only practical work in the block is a short activity in Section 2 in which you have to compare members of two 'samples' of similar objects. These 'samples' can be bags of potatoes, shelves of books, handfuls of stones or anything else that is convenient. Section 9 ends with a DVD-video activity 'Seeing inside the Sun' that shows how observations of our nearest star are used to understand the fundamental processes occurring deep within its interior. Finally, Section 11 contains another

DVD-multimedia package 'A history of the Universe' that draws together much of the material from this block.

In Section 11, therefore, there are two components to study — the book text and a DVD-multimedia package — and we have allocated a total of 4 hours for you to study them. You may wish to read through all the text and then use the DVD-multimedia package to investigate a few processes from the history of the Universe in more detail; or you may wish to spend several hours working through the DVD-multimedia package, only returning to the text at intervals as necessary. Alternatively you may find some other balance that suits you — you might wish to use the DVD-multimedia package to help you complete an assignment, or simply as a means of exploring the history of the Universe in greater detail than is possible within the text alone — the choice is yours. As you may realize, this DVD-multimedia package is rather different from the others you have met in the course. 'A history of the Universe' is not really an activity as such, it is a *resource* for you to use in a way that you find most appropriate.

As with earlier blocks, the Block 11 DVD includes a set of questions to enable you to consolidate your understanding of the material covered by the block.

Block 11 is assessed in part of TMA 09 and you should aim to complete the relevant question as soon as possible after you have completed your study of the block.

Before you embark on the block, a word of caution is in order. It is rather easy to get bogged down in the details of the processes and interactions that are discussed here, and you should be wary of falling into that trap. Instead, try to 'step back' at intervals and remind yourself of the overall themes that are covered. The section summaries will help you here, and you should use them frequently to make sure that you are concentrating on the main ideas rather than the incidental details.

11 Universal processes

All study times are in hours

Week	Sections of Book 11	Total study time	DVD-multimedia, DVD-video and practical activities
1	1 Introduction	$\frac{1}{2}$	
	2 The expanding Universe	4	 $\frac{1}{4}$  $\frac{3}{4}$
	3 The cooling Universe	1	
	4 Four fundamental interactions	$\frac{1}{2}$	
	5 Electromagnetic interactions	$2\frac{1}{2}$	
	6 Strong interactions	$1\frac{1}{2}$	
	7 Weak interactions	1	
	8 Gravitational interactions	1	
2	9 Four forces in the Sun	2	 $\frac{1}{2}$
	10 Unified theories	1	
	11 The evolving Universe	4	 4*
	12 The future of the Universe	1	

* As described overleaf, 4 hours is the total time to be spent on Section 11 and the DVD.

Summary of particles

leptons	charge	antileptons	charge	quarks	charge	antiquarks	charge
e^-, μ^-, τ^-	$-e$	e^+, μ^+, τ^+	$+e$	u, c, t	$+2e/3$	$\bar{u}, \bar{c}, \bar{t}$	$-2e/3$
ν_e, ν_μ, ν_τ	0	$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	0	d, s, b	$-e/3$	$\bar{d}, \bar{s}, \bar{b}$	$+e/3$

baryons	charge	composition	antibaryons	charge	composition	mesons	charge	composition
p	$+e$	uud	$\bar{p}$	$-e$	$\bar{u}\bar{u}\bar{d}$	π^+	$+e$	$u\bar{d}$
n	0	udd	$\bar{n}$	0	$\bar{u}\bar{d}\bar{d}$	π^-	$-e$	$d\bar{u}$
						π^0	0	$u\bar{u}$ or $d\bar{d}$

Study File for Block 11

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Notes on activities

You should read through the notes for each activity before attempting it. After completing an activity you should study the relevant comments in the next section of the Study File.

No estimate of time is given for activities which should take 10 minutes or less.

Activity 1.1 Revision: light and spectra

In much the same way as you revised Blocks 4 and 8 to help you in your study of Block 9, and/or Block 3 to help you in your study of Block 10, you may find that you need to look back to parts of Block 7 that you have studied earlier in the course to help you with your study of Block 11. In the first part of Block 11, astronomical spectra are discussed. To see if you need to revise your knowledge of light and spectra, try the following questions. If you have difficulty with any of them, follow the advice given in the comments on this activity.

Question 1.1.1 State what is meant by (a) an emission line spectrum and (b) an absorption line spectrum, and explain how such spectra are produced in each case. ◀

Question 1.1.2 (a) Describe the type of spectrum which is emitted by a metal when it is heated to a high temperature.

(b) Why is this type of spectrum produced?

(c) How will the spectrum alter as the temperature of the metal is increased? ◀

Question 1.1.3 (a) Which model of light is used to explain (i) its propagation and (ii) its interaction with atoms?

(b) Which are the two key equations that describe the behaviour of light in these two cases?

(c) Arrange the following types of electromagnetic radiation in order of (i) increasing photon energy, (ii) increasing wavelength and (iii) increasing frequency: blue light, gamma-rays, infrared radiation, yellow light, microwaves, radio waves, red light, ultraviolet radiation, X-rays. ◀

Activity 1.2 Revision: powers of ten

Throughout Block 11, very large and very small scales of distance, time and energy are discussed. These are naturally expressed in terms of positive and negative powers of ten. To see if you need to revise your knowledge of powers of ten, try the following questions. If you have difficulty with any of them, follow the advice given in the comments on this activity.

Question 1.2.1 (a) Arrange the following numbers in order of increasing size:

10^{-4} , 10^4 , 3×10^{-4} , 3×10^4 , 10^{-3} , 3×10^{-3} .

(b) How many times bigger than 10^{23} is 10^{25} ? ◀

Question 1.2.2 Calculate the following, *without using a calculator*:

(a) $(3.0 \times 10^7) - (2.0 \times 10^6)$

(b) $(3.0 \times 10^6) + (2.0 \times 10^7)$

(c) $(3.0 \times 10^6) \times (2.0 \times 10^7)$

(d) $(3.0 \times 10^7) \div (2.0 \times 10^6)$ ◀

Question 1.2.3 (a) What multiples do the prefixes k (kilo), M (mega) and G (giga) represent?

(b) Express an energy of 300 MeV as an equivalent value in both keV and GeV.

(c) Express an energy of 662 keV as an equivalent energy in joules.
(Hint: $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$.) ◀



Activity 2.1 Finding the typical member of a sample

For this activity you will need two 'samples' with at least twenty 'objects' in each sample. The important thing is that the samples contain similar types of things, but not necessarily the same number of objects in each sample, and that the objects in the sample have a range of different sizes. You could use two bags of the same sort of potatoes, or two handfuls of stones or gravel from the same path, or maybe two shelves of paperback books. (It won't work if you have one bag of large baking potatoes and another of small new potatoes!)

Having obtained your two samples, sort each of them into order from the largest to the smallest (or heaviest to lightest if that's easier to do). How do the largest (or heaviest) objects in each sample compare with each other? How do the *tenth* largest (or heaviest) in each sample compare? Do the tenth largest (or heaviest) objects in each sample represent a 'typical' member?

Activity 2.2 The virtual telescope



(The estimated time for this activity is 45 minutes.)

This DVD-multimedia activity takes the form of a virtual experiment. Unfortunately there is neither the time nor the funds to send every S103 student to a major astronomical observatory for a week of observations — the virtual telescope provides the next best thing.

You will have control of a powerful telescope with which you can measure the red-shifts and brightnesses of galaxies within several clusters. By converting the red-shifts into speeds of recession and by determining distances from the brightness measurements, you will be able to calculate a value for the Hubble constant. As you will see a little later in the block, the Hubble constant is a measure of the rate at which the Universe is currently expanding, and it also gives a measure of the age of the Universe.

In case you think that sitting in front of a computer is no substitute for visiting a real observatory, you might be surprised to learn that, even at a real observatory, professional astronomers usually spend the whole night sitting in front of a computer too. Thanks to the advent of electronic imaging devices, the days of peering through a telescope eyepiece are long gone at all of the big observatories.

In fact the telescope you'll be using has many advantages over the real thing. First, you don't have to travel half way around the world in order to use it. You're not gasping for breath at an altitude of over 4 000 m, and you don't have to stay awake all night. The telescope has an imager, a photometer (for measuring brightnesses) and a spectrometer (for obtaining spectra), each available at the click of a mouse button, and is available for use whenever you want it. In the real world, an application to use a telescope would be made a year in advance, and be subject to competition from hundreds of other astronomers. Only the very best applications get awarded a few nights at the telescope, and then the weather may be too bad to do anything. This telescope has perpetually cloud-free skies, and what's more you can see both the Northern and Southern Hemisphere skies from the same observatory. All in all this is a big improvement over a real telescope!

In your use of the virtual telescope, just as at a real observatory, you will be guided through the use of the telescope by a 'support astronomer'. This is a staff member of the observatory who is familiar with the operation of all the equipment and is always on hand to help visiting astronomers carry out their programme of observations.

'The virtual telescope' is on the Block 11 DVD. You should start this activity now. Note: As your results for the virtual telescope cannot be saved, you will need to complete the activity in a single session.

Enter your value for the Hubble constant here: _____

Then try the following question.

- ☐ Re-write the Hubble relationship $v = H_0 r$ using your value for H_0 . Remember to include the correct unit.
- If your value for H_0 was, say, $60 \text{ km s}^{-1} \text{ Mpc}^{-1}$ then the Hubble relationship may be written as

$$v = (60 \text{ km s}^{-1} \text{ Mpc}^{-1}) \times r \quad \text{or as} \quad v/\text{km s}^{-1} = 60r/\text{Mpc}$$

This is an equation of a straight line (see Block 7 Box 8.3) which passes through the origin. The line you fitted to the data produced using the virtual telescope should also have passed through the origin.

Activity 2.3 Understanding the Hubble relationship

(The estimated time for this activity is 15 minutes.)

(a) What are the red-shifts of clusters A, B and C in Figure 2.9 in the book as measured by an alien astronomer living on a planet, orbiting a star, in a galaxy in cluster D? (Hint: First determine the recession speeds in units of Mpc per billion years, then convert these into km s^{-1} . Finally use Equation 2.6 to calculate the red-shifts. You should use the approximations that $c = 3 \times 10^5 \text{ km s}^{-1}$, $1 \text{ Mpc} = 3 \times 10^{19} \text{ km}$, and that 1 year is equivalent to $3 \times 10^7 \text{ s}$. As indicated by these approximations, work to an accuracy of one significant figure in these calculations.)

(b) Using any of the three speeds you calculated in part (a), what is the value of the Hubble constant at the time identified as 'today' in this one-dimensional universe? Express your answer in units of $\text{km s}^{-1} \text{Mpc}^{-1}$.

(c) By carefully considering Figure 2.9, how does the value of the Hubble constant differ in the past and in the future of this one-dimensional universe from the value calculated in part (b)?

Activity 4.1 Revision: fundamental particles

The rest of Block 11 will build on many of the ideas about subatomic particles that you met in Block 7. To see if you need to revise your knowledge of fundamental particles, try the following questions. If you have difficulty with any of them, follow the advice given in the comments on this activity.

Question 4.1.1 (a) Name the six flavours of quark and six flavours of lepton, grouping each of them into three generations.

(b) State which combinations of quarks and antiquarks are found in hadrons, and give names to each type of combination.

(c) What is the quark composition of (i) a proton and (ii) a neutron? ◀

Question 4.1.2 (a) What are the antimatter counterparts of the following particles called: (i) electron, (ii) proton, (iii) down quark, (iv) electron neutrino.

(b) How do the properties of these antimatter particles differ from those of their matter counterparts? In what ways are their properties similar? ◀

Question 4.1.3 (a) A pion can be created in a particle accelerator if the kinetic energy available in the reaction is 140 MeV. What is the mass of a pion?

(b) In a particular radioactive decay process, the mass of the products is less than the mass of the parent nuclide by $5.2 \text{ MeV}/c^2$. How much energy is released in this decay? ◀

Activity 4.2 Planning your study time

You are now over one-quarter of the way through Block 11. The next half of the block (Sections 5–10) is concerned with the four fundamental interactions, and develops many of the ideas you will need for the final quarter of the block (Sections 11–12) concerning the history and future of the Universe. As you are nearing the end of the course, you may feel that you don't have enough time to study the whole of the block in detail. Now is a good time to decide how to allocate the time that you do have available.

Look at the Study Calendar and check when you are meant to complete this block. Remember that you are not allowed to submit TMA 09 (the final TMA of the course, assessing the second part of Block 7 and Block 11) late, and you will also need some time at the end of the year to prepare for the end-of-course assessment. This means that you will probably want to be up-to-date by the time you start reading Block 12.

Having looked at when you're meant to complete Block 11, make a realistic assessment of how much studying you have to do in the next week or so, and how much time you have available. Hopefully you will discover that you are up-to-date, or even ahead of schedule, but many students *are* a little behind at this time of year. If you have a lot of catching up to do, you may need to take some short cuts! Some suggestions are given in the comments on this activity.

Activity 5.1 The development of a theory

Figure 5.1.1 is a schematic representation of the development of the theory of quantum electrodynamics (QED). Each box gives the name of a theory and/or the name of the people responsible for particular developments mentioned in Section 5. In each box, write some notes to describe the phenomena predicted by the theory and/or by the people named.

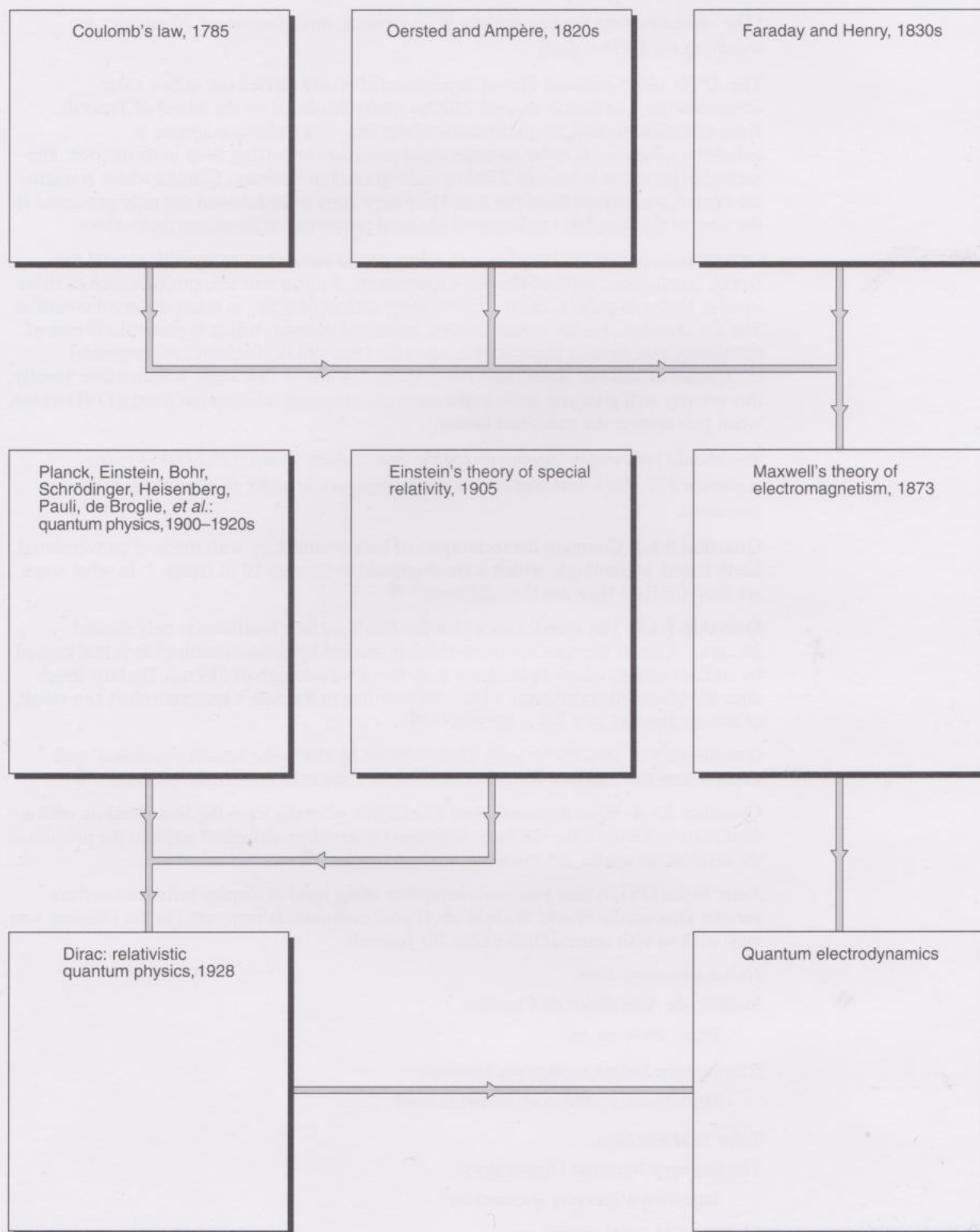


Figure 5.1.1 The development of the theory of quantum electrodynamics.

Activity 6.1 Dealing with difficult concepts

In Blocks 6 and 7 you practised study techniques to help you to get to grips with difficult concepts. You may be finding some of the concepts in Block 11 difficult too. If so, look back at the list of techniques and strategies that you compiled in the earlier blocks and think about which of the strategies might work in Block 11.



Activity 9.1 Seeing inside the Sun

(The estimated time for this activity is 30 minutes, including about 20 minutes for watching the DVD-video.)

This DVD-video presents film of experiments that are carried out at two solar observatories. The first is located 2 000 m above sea-level on the island of Tenerife. Here scientists investigate oscillations of the Sun — a technique known as helioseismology — in order to understand processes occurring deep in its interior. The second experiment is located 2 000 m underground in Sudbury, Canada where scientists are studying neutrinos from the Sun. Here they hope to understand not only processes in the core of the Sun, but fundamental physical properties of neutrinos themselves.

One purpose of this DVD-video is to allow you to see scientists at work around the world, conducting 'state-of-the-art' experiments. As you will see, projects such as these involve teams of people, often collaborating with colleagues in many different countries. The DVD-video also illustrates another feature of science, which is particularly true of astronomy and particle physics: it is often necessary to devise novel experimental techniques in order to investigate phenomena that are, at first sight, inaccessible. Finally, this activity will give you more experience of extracting information from a DVD-video, when you answer the questions below.

You should now watch 'Seeing inside the Sun', which is on DVD 2 (DVD-video sequence 377–456), and make notes while doing so, in order to answer the following questions.

Question 9.1.1 Compare the techniques of helioseismology with those of conventional, Earth based, seismology, which were discussed in Section 10 of Block 3. In what ways are they similar? How are they different? ◀

Question 9.1.2 The speed with which the Sun's surface oscillates is only around 20 cm s^{-1} . One of the spectral lines which is studied by helioseismologists is that caused by sodium atoms, which in the laboratory has a wavelength of 589 nm. By how much does the observed wavelength of this sodium line in the Sun's spectrum shift as a result of the oscillation? ($c = 3.0 \times 10^8 \text{ m s}^{-1}$) ◀

Question 9.1.3 Describe briefly what is meant by the 'solar neutrino problem' and explain how the Sudbury Neutrino Observatory hopes to resolve the problem. ◀

Question 9.1.4 What happens when an electron neutrino from the Sun interacts with a deuterium nucleus in the Sudbury Neutrino Observatory detector? Explain the process at the level of (a) nuclei, (b) nucleons, and (c) quarks. ◀

Note: In the DVD-video you see a computer being used to display information from various sites on the World Wide Web. If your computer is connected to the Internet, you may wish to visit some of these sites for yourself.

Helioseismology sites:

Instituto de Astrofísica de Canarias:

<http://www.iac.es/>

Birmingham Solar Oscillations Network:

<http://bison.ph.bham.ac.uk/index.html>

Solar neutrino sites:

The Sudbury Neutrino Observatory:

<http://www.sno.phy.queensu.ca>

Links to other solar neutrino sites:

<http://snodag.phy.queensu.ca/sno/experiments.html>

Activity 11.1 A history of the Universe



(The estimated time for this activity is between about 1 hour and 4 hours, depending on how you split your time between the DVD-ROM and the block.)

This DVD-multimedia package will help consolidate your understanding of the processes that have occurred since the Universe was created, from the Big Bang to the present day. Unlike most of the other DVD-multimedia activities in the course, it is a *resource* rather than an activity in its own right. Like the text in Section 11 of Block 11, it is presented as a story through time, with different processes identified as being important at each epoch. However, it may be studied in several ways:

- You may, if you wish, simply spend a couple of hours stepping through it in time, examining the processes that occurred at each point in the history of the Universe.
- Alternatively you may wish to use the package to compile the answer to an assignment or as a means of revising the material in the block. With this mode of use you can jump in at any epoch and examine the processes occurring, or you can select a particular process and look at when in the history of the Universe it was important, or you can search for a particular keyword and investigate the processes that are relevant to your search.

However you use this package, you will probably get the most from it if, on the first occasion you use it, you initially watch and listen to the summary. This presents a 'brief history of the Universe' and summarizes the many processes occurring from the Big Bang to the present day.

Since it is a resource, rather than an activity in itself, you may refer to the DVD-ROM at any point you wish during your study of Section 11. In order to get the most out of the package, you should try some of the following tasks, using the DVD-ROM and other components of the block to compile your answers. Most of these tasks are rather open-ended and you may wish to discuss your answers with other students or with your tutor.

'A history of the Universe' is on DVD 2.

Task 1

A hydrogen atom consists of a proton and an electron. Explain how protons and electrons are thought to have been created in the early Universe, and what conditions prevailed at these times. How and when did electrons attach to protons to form neutral hydrogen atoms?

Now look at the comment on Task 1 before continuing with Task 2.

Task 2

A star, like the Sun, contains a significant proportion of helium nuclei. Some of these nuclei were created within the star, others were formed early in the history of the Universe and were incorporated when the star originally formed. Explain how helium nuclei formed in each of these two cases. Pay particular attention to the conditions necessary for these processes to take place.

Task 3

Discuss the role of neutrinos in the Universe from the earliest times to the present day. Comment on how and when neutrinos were created, and how they are relevant to current studies of the Sun.

Task 4

Discuss the role of antimatter in the Universe from the earliest times to the present day. Why is there apparently very little antimatter in the Universe now?

Task 5

Some processes that are suggested as having occurred in the early Universe, when it was less than 10 s old, are rather uncertain. Describe some of the processes that may have occurred, and comment on how or why there is doubt concerning them.

Task 6

Discuss how equilibrium reactions have been important at various stages in the history of the Universe.

Task 7

Describe the particular processes that occurred in the Universe when it was (a) 10^3 , (b) 10^9 , and (c) 10^{15} times hotter than it is today.

Activity 11.2 The contents of the Universe

At the end of each of Sections 11.2–11.7, use Table 11.2.1 to make a note of what the contents of the Universe were at the time corresponding to the end of the period described in the section.

Table 11.2.1 The contents of the Universe at different times in its history.

Section	Time/s	Contents of the Universe
11.2 The very early Universe	10^{-36}	
11.3 Inflation	10^{-32}	
11.4 The quark–lepton era	10^{-5}	
11.5 The hadron era	100	
11.6 Primordial nucleosynthesis	1 000	
11.7 Structure in the Universe	today	

Activity 12.1 Science writing

(The estimated time for this activity is 30 minutes.)

This is another activity which requires you to read an article which was not specifically written for S103 students. You will be required to do this frequently in Block 12 and more guidance is given there.

The article we have supplied on this occasion was written for an informed but not scientifically trained audience. We would like you to apply what you have learnt in Block 11 to this article. The article was written by Professor Martin Rees, the Astronomer Royal, and is an edited extract of his Darwin Lecture in 1995. Read through the article in Appendix 1 now and then answer the following questions.

- Which aspects of the discussion in Block 11 are supported by the information in the article?
- What new information about the history of the Universe have you gained from the article?
- Which aspects of Block 11 are refuted by the article?

Writing your answer in note form is appropriate. The comments for this activity discuss the relevant information.

Activity 12.2 New discoveries

This block was written in early 1998 and for some of the speculative or uncertain topics discussed here we remarked that they may be confirmed, or quantities measured more accurately, within the lifetime of the course.

Here is one example. In June 2001, scientists from the Sudbury Neutrino Observatory in Canada presented new findings about neutrinos. Neutrinos created deep inside the Sun can change from one type into another as they stream towards Earth. The shortfall in the number of solar neutrinos observed in the last 30 years has cast doubt on the so-called standard solar model (see Question 9.1.3 in this study file). However, the new results confirm instead that electron neutrinos can 'oscillate' into muon and tau neutrinos and vice versa. Such oscillations can occur only if neutrinos have mass.

Make a list of other things that we identify as speculative, and the quantities that are poorly known, and discuss with your tutor or other S103 students whether knowledge regarding them has changed since early 1998.

Comments on activities

Activity 1.1

Question 1.1.1 (a) An emission line spectrum is a spectrum that consists of light of only specific colours (or energies or wavelengths or frequencies). The emission lines are produced when atoms make transitions from higher energy levels to lower energy levels, and emit photons whose energy corresponds to the difference in energy between the two energy levels. This situation exists, for example, in a vapour which is excited by passing an electric current through it.

(b) An absorption line spectrum is a spectrum in which certain colours (or energies or wavelengths or frequencies) are absent. The absorption lines are produced when atoms absorb photons whose energy corresponds to the difference in energy between two energy levels. The atoms make transitions from lower energy levels to higher energy levels as a result. This situation exists, for example, when radiation with a continuous spectrum is passed through a cool vapour.

{If you had difficulty answering this question, it might be worth re-reading Section 2 and Section 7 of Block 7. To save time you could just re-read the summaries of these sections, or your own notes on them.}

Question 1.1.2 (a) A hot metal will emit a continuous spectrum consisting of light of all colours (or energies or wavelengths or frequencies).

(b) A continuous spectrum is emitted because the metal has a great many energy levels with small energy differences between them. Transitions between these energy levels allow photons with a continuous range of energy to be emitted.

(c) As the temperature of the metal is increased, it will still emit a continuous spectrum of radiation, but the mean energy of the photons will increase. As a result, the metal will change colour, from red to yellow for instance, as it is heated up.

{If you had difficulty answering this question, have another look at Figure 1.3, Section 2.7 and Section 7 of Block 7.}

Question 1.1.3 (a) (i) The wave model. (ii) The particle model (i.e. photons).

(b) $c = f\lambda$ and $E_{ph} = hf$, where c is the speed of light, f is the frequency and λ the wavelength of the wave used to describe its propagation, E_{ph} is the photon energy and h is the Planck constant.

(c) (i) In order of increasing photon energy: radio waves, microwaves, infrared radiation, red light, yellow light, blue light, ultraviolet radiation, X-rays, gamma-rays.

(ii) In order of increasing wavelength: gamma-rays, X-rays, ultraviolet radiation, blue light, yellow light, red light, infrared radiation, microwaves, radio waves.

(iii) In order of increasing frequency: radio waves, microwaves, infrared radiation, red light, yellow light, blue light, ultraviolet radiation, X-rays, gamma-rays.

{Note that the orders in (i) and (iii) are identical because $E_{ph} \propto f$. The order in (ii) is exactly the opposite because $E_{ph} \propto 1/\lambda$. If you had difficulty answering this question,

have another look at Block 7 Figures 2.6, 2.8 and 8.9 and re-read the summaries of Sections 7, 8 and 9 in Block 7.}

Activity 1.2

Question 1.2.1 (a) In order of increasing size:

$$10^{-4}, 3 \times 10^{-4}, 10^{-3}, 3 \times 10^{-3}, 10^4, 3 \times 10^4.$$

(b) Since $\frac{10^{25}}{10^{23}} = 10^{(25-23)} = 10^2$, then 10^{25} is 100 times bigger than 10^{23} .

{If you had difficulty answering this question, look again at Block 1 Boxes 6.1 and 6.2 or at the section entitled 'Powers and scientific notation' on the Block 1 DVD.}

Question 1.2.2

$$(a) (3.0 \times 10^7) - (2.0 \times 10^6) = (3.0 \times 10^7) - (0.2 \times 10^7) = 2.8 \times 10^7$$

$$(b) (3.0 \times 10^6) + (2.0 \times 10^7) = (0.3 \times 10^7) + (2.0 \times 10^7) = 2.3 \times 10^7$$

$$(c) (3.0 \times 10^6) \times (2.0 \times 10^7) = (3.0 \times 2.0) \times 10^{(6+7)} = 6.0 \times 10^{13}$$

$$(d) (3.0 \times 10^7) \div (2.0 \times 10^6) = \left(\frac{3.0}{2.0}\right) \times 10^{(7-6)} = 1.5 \times 10^1 = 15$$

{If you had difficulty answering this question, look again at Block 2 Box 6.2 or at the section entitled 'Powers and scientific notation' on the Block 1 DVD.}

Question 1.2.3 (a) kilo = 10^3 , mega = 10^6 , giga = 10^9

$$(b) 300 \text{ MeV} = 300 \times 10^3 \text{ keV} = 3 \times 10^5 \text{ keV}$$

$$\text{and } 300 \text{ MeV} = 300 \times 10^{-3} \text{ GeV} = 0.3 \text{ GeV}$$

$$(c) 662 \text{ keV} = (662 \times 10^3 \text{ eV}) \times (1.60 \times 10^{-19} \text{ J eV}^{-1}) = 1.06 \times 10^{-13} \text{ J}$$

{If you had difficulty answering this question, look again at Block 2 Box 3.2 which deals with the prefixes mega and giga, and Block 1 Box 3.1 which deals with kilo.}

Activity 2.1

I used two bags of potatoes from the supermarket. Each bag contained the same type of potato, but there were more in one bag than the other. After sorting the potatoes from each bag into size order, I found that the largest potatoes in each bag were quite different. One bag had a very large, largest potato indeed. So the largest member of a sample is not a 'typical' object and is not suitable for comparison with other samples. However, the tenth largest potatoes in each bag were remarkably similar in size and shape. The tenth largest is a 'typical' member of each sample, irrespective of the number of objects in that sample. Similar results will apply to many samples of objects — not least galaxies in clusters!

Activity 2.2

The Hubble constant is simply the gradient of the graph of recession speed against distance for a number of clusters of galaxies.

A typical value for the Hubble constant obtained from this activity is around $60 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In practice, different astronomers using different methods find values for H_0 that range from about 40 to $80 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The 'true' value is likely to be somewhere within this range.

In Section 2.6 you will use your value of the Hubble constant to estimate the age of the Universe.

Activity 2.3

(a) The speeds of recession of clusters A, B and C as measured from cluster D are 3 Mpc per billion years, 7 Mpc per billion years and 8 Mpc per billion years, respectively. The next step is to convert these speeds into km s^{-1} .

1 Mpc is equivalent to $3 \times 10^{19} \text{ km}$; and one billion years is equivalent to $(10^9 \text{ years}) \times (3 \times 10^7 \text{ seconds per year}) = 3 \times 10^{16} \text{ s}$. So a speed of 1 Mpc per billion years is roughly equal to $\left(\frac{3 \times 10^{19} \text{ km}}{3 \times 10^{16} \text{ s}} \right) = 1000 \text{ km s}^{-1}$. The

recession speeds of the three clusters are therefore 3000 km s^{-1} , 7000 km s^{-1} and 8000 km s^{-1} , respectively.

Using Equation 2.6, the red-shift is given by $z = v/c$, where $c = 3 \times 10^5 \text{ km s}^{-1}$. So, the red-shifts of the three clusters, as measured from cluster D, are:

$$z_A = \left(\frac{3000 \text{ km s}^{-1}}{3 \times 10^5 \text{ km s}^{-1}} \right) = 0.01$$

$$z_B = \left(\frac{7000 \text{ km s}^{-1}}{3 \times 10^5 \text{ km s}^{-1}} \right) = 0.02$$

$$z_C = \left(\frac{8000 \text{ km s}^{-1}}{3 \times 10^5 \text{ km s}^{-1}} \right) = 0.03$$

(b) Using any of the three speeds from part (a), the Hubble constant at the time identified as 'today' is found from Equation 2.7 as the recession speed divided by the distance, $H_0 = v/r$. So, for the measurement of cluster C from cluster D,

$$H_0 = \left(\frac{8000 \text{ km s}^{-1}}{80 \text{ Mpc}} \right) = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

The Hubble constant is measured with the same value (at the same time), *wherever* you happen to be in this one-dimensional universe, and this is true of the universe that we find ourselves in too. The value of the Hubble constant calculated here is, however, somewhat higher than the current value in our Universe.

(c) At times in the past of this one-dimensional universe, clusters of galaxies were closer together, but moving apart at the same speed. So the Hubble constant at earlier times was *larger* than it is at the time identified as 'today'. Conversely, at times in the future of this one-dimensional universe, clusters of galaxies are farther apart, but still moving at the same speed. So the Hubble constant at later times will be *smaller* than it is at the time identified as 'today'.

In order to appreciate this more quantitatively, consider the value of the Hubble constant at $t = 9$ billion years. The speed of recession of (say) cluster C from cluster D is 8000 km s^{-1} , as calculated in part (a), and this value is the same whatever time we choose to measure it. The two clusters are 72 Mpc apart at this time. So the Hubble constant at this time is

$$H_{\text{past}} = \left(\frac{8000 \text{ km s}^{-1}}{72 \text{ Mpc}} \right) = 110 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

We have quoted this answer to two significant figures to make it clear that it is larger than it is at the time identified as 'today'. Conversely, at $t = 11$ billion years, clusters C and D are 88 Mpc apart, so the Hubble constant at this time is

$$H_{\text{future}} = \left(\frac{8000 \text{ km s}^{-1}}{88 \text{ Mpc}} \right) = 90 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

to one significant figure, which is smaller than it is at the time identified as 'today'.

Notice that in this universe, even though any particular pair of clusters of galaxies continue travelling apart at the same speed, the rate of expansion of the intervening space becomes progressively smaller. The Hubble constant quantifies the expansion rate of the Universe, and clearly the expansion rate of this one-dimensional universe is slowing down. A similar effect occurs in our own Universe — the Hubble constant is not the same at different times.

Activity 4.1

Question 4.1.1 (a) The six flavours of quark are: up and down (first generation), charm and strange (second generation), top and bottom (third generation).

The six flavours of lepton are: electron and electron neutrino (first generation), muon and muon neutrino (second generation), tauon and tauon neutrino (third generation).

(b) A hadron can consist of three quarks (in which case it is called a baryon), or three antiquarks (in which case it is called an antibaryon), or a quark and an antiquark (in which case it is called a meson).

(c)(i) A proton is composed of two up quarks and a down quark (uud). (ii) A neutron is composed of two down quarks and an up quark (udd). (Both are baryons.)

{If you had difficulty answering this question, re-read the summary of Section 6 in Block 7, and the relevant glossary entries.}

Question 4.1.2 (a) The antimatter counterparts are as follows: (i) antielectron (or positron); (ii) antiproton; (iii) antidown quark; (iv) electron antineutrino.

(b) Antimatter particles have the opposite electric charge to their matter counterparts, and antimatter baryons (antibaryons), such as the antiproton, are composed of antiquarks. The corresponding matter and antimatter particles have the same mass as each other.

{If you had difficulty answering this question, re-read Block 7 Box 5.1.}

Question 4.1.3 (a) The pion has a mass of $140 \text{ MeV}/c^2$.

(b) An energy of 5.2 MeV is released in this decay.

{If you had difficulty answering this question, re-read Section 5.1 in Block 7 which deals with mass and energy conversions and Einstein's equation $E = mc^2$.}

Activity 4.2

If you are short of time, there are parts of this block that you can skim through quickly without missing out the material necessary to understand the culmination of this block in Sections 11 and 12.

Most of Sections 8 and 9, concerning gravity and the role of the four fundamental interactions in the Sun, is not revisited in later sections. As a result, your study of Sections 11 and 12 will not suffer unduly if you simply read the summaries of Sections 8 and 9. However, the material in these sections is conceptually less demanding than that in Sections 5–7, and includes an interesting DVD-video, so you will miss out on the chance to 'take a breather' from the more difficult material if you follow this course of action.

Another approach you could take is, rather than writing down the answers to some of the questions in the next few sections, simply think about how you would answer them before turning to the answers to read the detailed comments provided there. This will save you some time, but will mean you have less practice with questions of this type.

Finally, if you are still short of time as you approach the end of the block, you may choose not to look at the final DVD package 'A history of the Universe' and rely only on the material presented in Section 11 of the block. Again, you may find the DVD material easier going than some of the block text, but it is probably quicker to read the material in the block than access it on the DVD. (If you go for this option, hopefully you will find time to look at the package at a later date.)

With all these strategies for saving time, you are bound to miss out on some important aspect of Block 11. We have designed the block to be an integrated whole, and therefore all parts of it are interconnected and rely on what has gone before. Nonetheless, the suggestions above may help you to save time in the run-up to the end-of-course assessment.

Activity 5.1

Figure 5.1.2 (on page 13) is a completed version of Figure 5.1.1 showing the sort of thing you may have written in the boxes.

{You may find this type of diagram useful for collecting together information and making links between it. You can construct similar diagrams for other sections.}

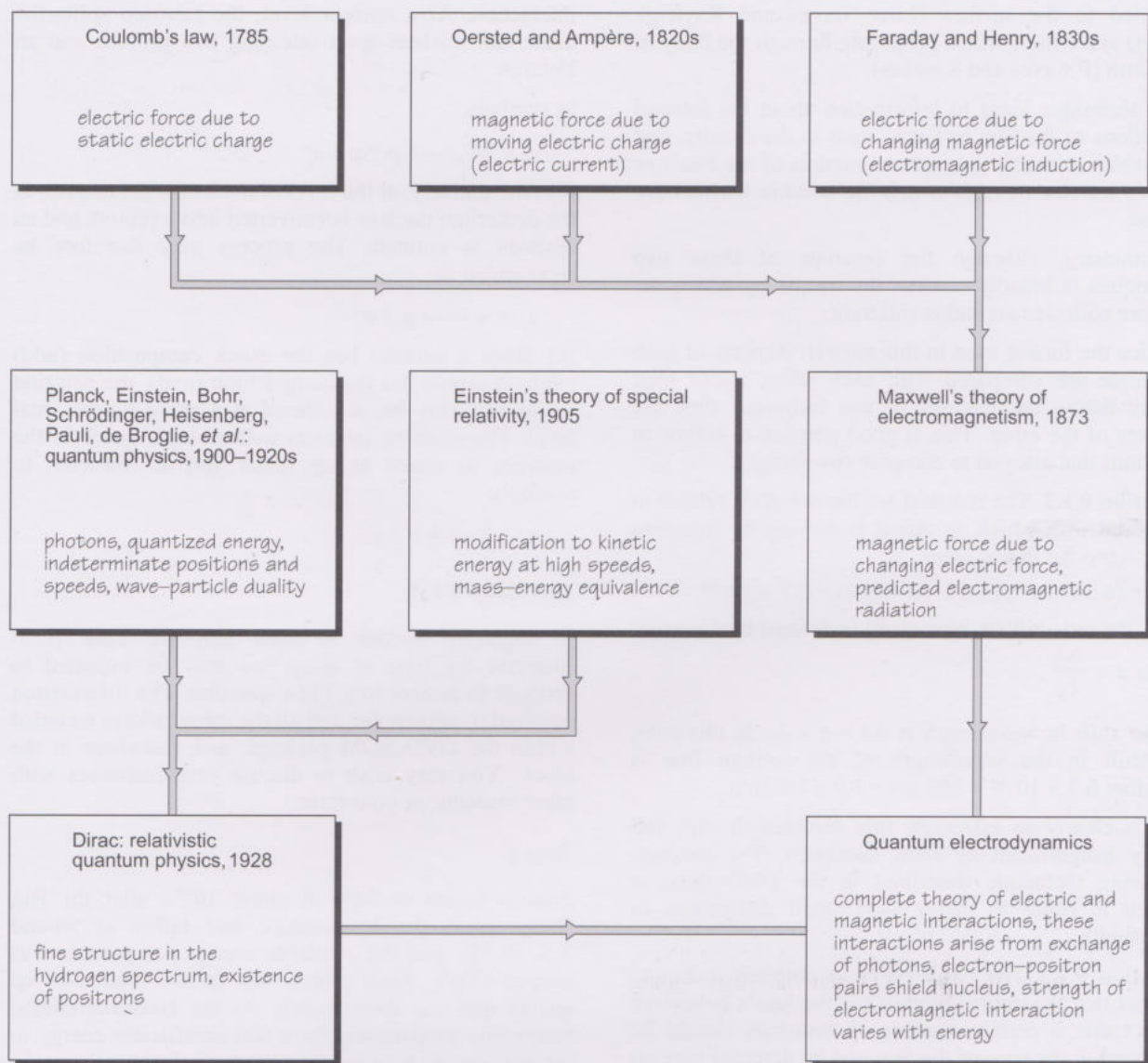


Figure 5.1.2 The development of the theory of quantum electrodynamics.

Activity 6.1

The techniques for understanding suggested in Block 6 included drawing a diagram and representing the situation by a simplified model. Unfortunately the sizes we're considering in Block 11 are almost unimaginably big or small, and most people find diagrams and models less helpful in this situation. Your other strategies from Blocks 6 and 7 will still help here though, and you may have developed further strategies during your study of the subsequent blocks.

It is also perhaps worth just pausing to reflect on how your ability to cope with new concepts has improved since you started S103 less than a year ago. You are now reading about theories which have only recently been developed, and in the rest of Block 11 and in Block 12 you are reminded that discoveries in these areas are likely to be made at around the time you are reading the course. This is 'cutting-edge science'.

Activity 9.1

Question 9.1.1 Both techniques measure the motion of the surface, either of the Sun or the Earth. In each case this motion is caused by seismic waves, generated either deep inside the Sun, or by earthquakes in the Earth's crust. These seismic waves propagate through the interior of the Sun or Earth and can be detected over the whole surface.

In the case of the Sun, the oscillations are detected using sophisticated spectroscopic techniques. The slight motion of the Sun's surface means that it alternately moves towards and away from us. This changing speed of motion results in tiny Doppler shifts in the spectral lines that are present in the solar spectrum. By measuring the variation in wavelength of these lines, the speed and period of oscillation of the Sun's surface can be determined, and the different components (harmonics) can be identified. In the case of the Earth, the surface motion can be detected directly, for instance by the movement of objects in contact with the Earth. In this case, it is the amplitude and arrival times of the seismic waves that are usually measured. Four principal types of seismic waves are recognized, two of which are

confined to the surface (Love waves and Rayleigh waves) and two of which propagate through the body of the Earth (P waves and S waves).

Each technique leads to information about the internal conditions of the Sun or Earth, such as the density, and so enables scientists to construct models of the Sun's or Earth's interior through which the seismic waves have passed.

In summary, although the outcome of these two techniques is broadly similar, the means by which the data are collected are rather different.

{Notice the format used in this answer. Aspects of each technique are compared with each other, rather than simply listing the features of one technique then the features of the other. This is good practice to follow in questions that ask you to compare two things.}

Question 9.1.2 The red-shift (or blue-shift) is related to the speed with which an object is moving by Equation 2.6, $z = v/c$. So in this case

$$z = (0.20 \text{ m s}^{-1}) / (3.0 \times 10^8 \text{ m s}^{-1}) = 6.7 \times 10^{-10}$$

Now, the red-shift (or blue-shift) is defined by Equation

$$2.5 \text{ as } z = \frac{\Delta\lambda}{\lambda_0}.$$

So the shift in wavelength is $\Delta\lambda = z \times \lambda_0$. In this case, the shift in the wavelength of the sodium line is therefore $6.7 \times 10^{-10} \times 589 \text{ nm} = 3.9 \times 10^{-7} \text{ nm}$.

This is clearly an extremely tiny wavelength shift and utterly insignificant by most standards. The resonant scattering technique described in the DVD-video is needed in order to detect such small differences in wavelength.

Question 9.1.3 The 'solar neutrino problem' refers to the fact that theoretical models for the Sun's behaviour predict that a certain number of neutrinos should be produced in the core of the Sun and be detected here on Earth. The problem is that far fewer neutrinos are detected than are predicted. Either our understanding of the Sun is wrong, or there is something wrong with existing experiments, or our understanding of neutrinos is insufficient.

The Sudbury Neutrino Observatory experiment, unlike other neutrino detectors, is sensitive to all three flavours of neutrino (electron neutrino, muon neutrino, and tauon neutrino). Although the Sun is predicted to *produce* only electron neutrinos, if neutrinos have mass then they can change flavour on their journey between the Sun and the Earth. If this happens it would explain why previous detectors have found fewer neutrinos than expected, since they were sensitive only to electron neutrinos and would have missed the other types if they were present. The Sudbury experiment was designed to measure the total number of all types of neutrino received from the Sun, and so hopefully resolve the 'solar neutrino problem'. Since the video was made, SNO has indeed detected muon and tauon neutrinos. The result, announced in 2001, shows that (i) the total number of neutrinos emitted by the Sun matches that predicted by theory, (ii) some of the electron neutrinos change to muon and tauon neutrinos as they travel through space, and (iii) neutrinos must have mass.

Question 9.1.4 (a) When an electron neutrino interacts with a deuterium nucleus, the process relies on the weak

interaction. At a nuclear level, the neutrino splits the deuterium nucleus apart releasing two protons and an electron.

In symbols:



(b) Alternatively, at the level of nucleons, the neutron in the deuterium nucleus is converted into a proton, and an electron is emitted. The process may therefore be represented as:



(c) Since a neutron has the quark composition (udd) whilst a proton has the composition (uud), the neutrino interaction may be considered at a more fundamental level. The neutrino interacts with a down quark in the neutron, to create an up quark and an electron. In symbols:



Activity 11.1

A suggested answer is given only for Task 1, to illustrate the type of thing you may be expected to produce in answer to a TMA question. The information required to answer this and all the other tasks is included within the DVD-ROM package, and elsewhere in the block. You may wish to discuss your responses with other students, or your tutor.

Task 1

Protons began to form at about 10^{-5} s after the Big Bang, when the temperature had fallen to around $3 \times 10^{12} \text{ K}$, and the available energy per particle was around 1 GeV. Each proton was formed from two up quarks and one down quark. As the Universe cooled below this temperature, there was insufficient energy to separate quarks by more than the typical dimensions of a hadron, and so the quarks remained confined from here on.

Electrons were formed much earlier. In the earliest times of which we can speak, electrons (along with all other leptons) were formed either in pair creation processes, or from the decay of X bosons. At this time, the available energy was far higher than can be achieved in current particle accelerators. Later, at times between about 10^{-11} s and 10^{-5} s , when the available energy per particle fell from 1 000 GeV to 1 GeV, further electrons were formed as a result of the decays of massive quarks and leptons. When the Universe was about 10 s old, and the available energy per particle fell below about 1 MeV, most of the electrons mutually annihilated with positrons, leaving just one-in-a-billion behind to balance the electric charge of the protons in the Universe.

As the available energy per particle fell below a few tens of electronvolts, when the Universe was a few hundred years old, electrons began to attach to protons to form neutral hydrogen atoms. When the Universe reached an age of 300 000 years, the energy per particle fell below 1 eV, and no photons had enough energy to ionize the hydrogen atoms. From here on, the neutral hydrogen atoms were able to become incorporated into stars and participate in nucleosynthesis to produce all the other elements in the Universe.

Activity 11.2

The contents of the Universe at the various times corresponding to the end of each section are given in Table 11.2.2.

Table 11.2.2 Completed version of Table 11.2.1. The contents of the Universe at different times in its history.

Section	Time/s	Contents of the Universe
11.2 The very early Universe	10^{-36}	six flavours of quark, six flavours of lepton, X bosons, photons (and presumably gluons, gravitons, W and Z bosons too)
11.3 Inflation	10^{-32}	the same as above, except that X bosons had largely disappeared
11.4 The quark-lepton era	10^{-5}	up and down quarks, electrons, positrons, neutrinos and antineutrinos, photons
11.5 The hadron era	100	protons, neutrons, electrons, neutrinos and antineutrinos, photons
11.6 Primordial nucleosynthesis	1 000	mainly hydrogen and helium nuclei; traces of deuterium, helium-3, and lithium-7 nuclei; electrons, neutrinos and antineutrinos, photons
11.7 Structure in the Universe	today	galaxies, stars, gas and dust (all of which are made of molecules and atoms, the vast majority of which are hydrogen and helium); photons (cosmic microwave background) fill all space; neutrinos and antineutrinos still present but almost undetectable

Activity 12.1

The article by Martin Rees clearly covers much of the same ground as the material in Block 11. Most of the things mentioned in the article should be familiar to you from your reading of this block. For instance, he discusses the idea of a Big Bang and the evidence for it provided by Penzias and Wilson's discovery of the 3 K cosmic microwave background, and the recent accurate measurements of the spectrum of this radiation by COBE. He also refers to the relative abundances of hydrogen, helium and other light elements, produced soon after the Big Bang, that you have read about. The possible future fates of the Universe (heat death or big crunch) are mentioned, as are the ideas about the proportions of visible matter and dark matter in the Universe. He also describes the inflationary model for the early Universe and discusses why it helps to solve the problem of the 'smoothness' of the Universe. There is a discussion of the formation of the Sun and other stars, the nucleosynthesis occurring within their cores, and the end point of evolution for many stars as supernovae in which massive nuclei are created and thrown out into space. All of these concepts should by now be familiar to you.

Some of the new ideas mentioned in the article are the detail given about the future evolution of the Sun as a red giant, the development of an 'onion skin' structure of concentric shells each undergoing different nuclear fusion reactions, and the ultimate fate of the Sun as a white dwarf. The idea that massive stars evolve more quickly than low mass stars may also be new to you. Other points not covered in Block 11 are the fact that 1% of the 'noise' on a TV picture is due to the cosmic microwave background, the fact that the Andromeda Galaxy will ultimately merge with our own Galaxy, and

the relative abundances of different elements in the Universe. The discussion about the 'thermodynamics' of the Universe is also somewhat beyond the scope of material presented in this course.

As for information in Block 11 that is refuted by the article, there is really very little (as you would hope!). The article often refers to the age of the Universe as about 10 billion years, but this merely reflects the uncertainty with which the age is known. The value we have used (11 billion years) is equally likely. Block 11 states that the critical density is about four protons per cubic metre, whereas the article uses a figure of three atoms per cubic metre. Again, this discrepancy is down to uncertainty in the current value of the Hubble constant. Another small discrepancy is that the article mentions that the density of visible matter falls short of the critical density by a factor of 50, whereas we have said that visible matter constitutes only about 1% of the critical density. This serves to illustrate the uncertainties that exist in this speculative subject. Finally, the article mentions that the cosmic microwave background is a relic of the time half a million years after the Big Bang, whereas Block 11 refers to this time as 300 000 years after the Big Bang. On the time-scales we have been considering here, this difference is too small to matter.

Although the article by Martin Rees is aimed at a general audience, you probably feel that you have got a lot more out of the article, as a result of reading Block 11, than you would have done had you read the article without this benefit.

Activity 12.2

Some of the speculative topics that you may have listed include:

What are the true values of the Hubble constant and the age of the Universe?

Have gravitational waves been detected?

Has a theory of quantum gravity been developed?

Has the Higgs boson been detected?

Has evidence for proton decay been observed?

Do neutrinos change flavour and if so what are their masses?

Is the Universe open, closed or flat?

If the Universe is flat, what is the missing matter composed of?

Have any of these questions been answered in recent years?

Further reading

Barrow, J. D. (1995) *The Origin of the Universe*, Weidenfeld and Nicholson. This is a very readable account of the current state of knowledge concerning cosmology and the Big Bang. It is written at a level similar to that of S103, and does not rely on any mathematics.

Cadogan, P. H. (1985) *From Quark to Quasar: Notes on the scale of the Universe*, Cambridge University Press. A visually stunning book that takes the reader on a tour from the everyday scale, first out to the limits of the Universe, and second down to the invisible world of quarks. Most 'powers of ten' on the distance scale from the horizon distance of the Universe down to the Planck length are illustrated.

Charlesworth, K. and Gribben, J. (1990) *The Cartoon History of Time*, Macdonald & Co. The best way to describe this book is to use the phrases of the authors themselves. They claim that it 'Refreshes the parts other time histories cannot reach' and that it is the 'definitive study of life, the Universe and (almost) everything'. They could be right! And it's certainly worth reading for an alternative presentation of the theories behind cosmology and particle physics.

Davies, P. C. W. (1995) *The Last Three Minutes*, Weidenfeld and Nicholson. This is another in the same series as Barrow's book (see above), addressing the question of the fate of the Universe. The two together provide an excellent overview of the topic by two of the foremost popular science writers in the field.

Davies, P. C. W. (ed.) (1989) *The New Physics*, Cambridge University Press. This book provides an extensive survey of the current state of physics. It covers such topics as astrophysics, cosmology and general relativity, quantum physics, quantum gravity, particle physics and grand unified theories, and also such themes as superconductivity and chaos theory that are outside the scope of Block 11 but nonetheless interesting for that. Each chapter is clearly and concisely written by an expert in the field. Mathematical explanations are reserved for boxes at the end of each chapter.

Davies, P. C. W. (1982) *The Accidental Universe*, Cambridge University Press. This book addresses the big question of the purpose of the Universe. By examining the mysterious coincidences that underlie the structure and properties of the Universe, Davies tackles the question of whether the Universe is one vast accident of nature, or whether in some sense, it had to happen.

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Objectives for Block 11

The objectives state what you should understand and what you should be able to do after studying the block.

The numbers of questions and activities that test each objective are given in italics. In the margin next to some objectives are references to *The Sciences Good Study Guide (SGSG)*, giving the chapter: section number or Maths Help (MH) number, where you can find additional support.

Science content

- 1 Explain the meaning of, and use correctly, all the terms printed in **bold** in the text.
- 2 Cite three pieces of evidence which support the hot big bang model for the origin of the Universe. (*Questions 11.1 and 11.15; Activities 2.2, 2.3 and 11.1*)
- 3 Explain how the speeds and distances of galaxies are determined, and calculate recession speeds, red-shifts, brightnesses, and distances of galaxies, given appropriate data. (*Questions 2.1–2.8; Activities 2.1–2.3 and 11.1*)
- 4 Describe how black-body spectra arise and explain the origin and significance of the cosmic microwave background radiation. (*Questions 3.1–3.3; Activities 1.1 and 11.1*)
- 5 Characterize the four fundamental interactions according to their strength, their participants, and the quanta that are exchanged. (*Questions 4.1, 5.1–5.7, 6.1–6.4, 7.1–7.3, 8.1–8.3, 10.1–10.4, 11.1 and 11.6; Activity 11.1*)
- 6 Use Feynman diagrams to represent particle interactions. (*Questions 6.3 and 7.1*)
- 7 Explain the importance of dimensionless numbers in characterizing the strength of fundamental interactions. (*Questions 5.2, 6.3 and 7.3*)
- 8 Describe current attempts to produce unified theories of the four fundamental interactions. (*Questions 10.1–10.4; Activity 11.1*)
- 9 Identify roles played by each of the four interactions in processes in stars, and the Sun in particular. (*Questions 9.1–9.3; Activity 9.1*)
- 10 Sort into time order events in the history of the Universe. (*Questions 11.11–11.15; Activities 11.1 and 11.2*)
- 11 Describe the role of inflation in the very early Universe. (*Questions 11.3–11.5; Activity 11.1*)
- 12 Understand how the contents of the Universe came to be as they are today as a result of particle interactions in the early Universe. (*Questions 11.2 and 11.6–11.14; Activities 4.1, 11.1 and 11.2*)
- 13 Describe the possible future behaviour of the Universe. (*Questions 12.1 and 12.2*)
- 14 Recall the meaning of the following equations, and use them correctly:

$$r = \sqrt{\frac{L_{10}}{4\pi F_{10}}} \quad (\text{Questions 2.3 and 2.4; Activity 2.2})$$

$$z = \frac{\Delta\lambda}{\lambda_0} \quad (\text{Questions 2.5 and 2.6; Activity 2.2})$$

$$z = \frac{v}{c} \quad (\text{Questions 2.5–2.7; Activities 2.2 and 2.3})$$

$$v = H_0 r \quad (\text{Questions 2.7 and 2.8; Activities 2.2 and 2.3})$$

$$E_{\text{ph, mean}} = 2.7kT \quad (\text{Questions 3.1–3.3})$$

$$F_e = -k_e \frac{Q_1 Q_2}{r^2} \quad (\text{Questions 5.1, 5.5 and 6.1})$$

$$F_m = k_m \frac{2I_1 I_2 L}{r} \quad (\text{Questions 5.3–5.5})$$

$$F_g = G \frac{m_1 m_2}{r^2} \quad (\text{Questions 8.1 and 8.2})$$

Science skills

- 15 Use a statistical argument to find the 'typical' member of a sample. (*Activity 2.1*)
- 16 Use a flow diagram to chart the development of a scientific idea. (*Activity 5.1*)

Communicating science skills

- 17 Use symbols and equations to communicate scientific ideas. (*Most questions and activities involving calculations*) SGSG MH9
- 18 Present written answers to numerical questions in an appropriate way. (*Most questions and activities involving calculations*) SGSG 4: 5
- 19 Relate parts of a published article to parallel explanation in the course. (*Activities 12.1 and 12.2*)

Mathematical skills

- 20 Rearrange and combine algebraic equations in order to calculate a desired quantity from other known quantities. (*Questions 2.4–2.8, 3.2, 3.3, 5.1–5.7, 6.1, 6.2, 8.1, 8.2 and 10.3; Activity 2.3*) SGSG MH9
- 21 Use the parsec (pc) as a unit of astronomical distance. (*Questions 2.1, 2.4 and 2.7; Activity 2.2*)
- 22 Use the electronvolt (eV) as a unit of energy and the electronvolt/ c^2 (eV/ c^2) as a unit of mass. (*Questions 5.6, 6.2, 6.3, 7.3, 9.1 and 10.1–10.3; Activities 4.1 and 11.1*)
- 23 Perform calculations involving orders of magnitude. (*Questions 5.1, 5.7, 6.1, 7.2, 10.2 and 11.3*)
- 24 Perform calculations using very large and very small powers of ten. (*Many questions and Activity 1.2*)
- 25 Perform calculations involving raising a number to a certain power. (*Question 7.2*)

Effective learning skills

- 26 Use a DVD-ROM-based resource to find the information needed to answer questions. (*Activity 11.1*)
 - 27 Review and reflect on various study and learning techniques. (*Activity 6.1*) SGSG 1: 4
 - 28 Revise material presented earlier in the course. (*Activities 1.1, 1.2 and 4.1*)
 - 29 Plan your study time effectively. (*Activity 6.1*)
-

Acknowledgement

Grateful acknowledgement is made to the following source for permission to reproduce material in this study file:

Rees, M. 1995, 'Universal picture', *Times Higher Educational Supplement*, 30 June 1995, © Times Supplements Limited, 1995.

Appendix 1 What to do if you are short of time

This brief guide to the activities in Block 11 should help you to decide for yourself whether you need to do a particular activity. Remember, though, that if you have the time you should aim to do *all* the activities in order to obtain the full benefit from your study.

The four numbered columns in the table below offer advice about each activity as follows:

- 1 essential that you do this activity at the particular point in Book 11 where it appears;
- 2 important, but there is more flexibility about when you do this activity, although you should try to complete it before moving onto the next section of Book 11;
- 3 may not be essential if you have some background already in the topic or skill, or have found earlier, similar activities straightforward;
- 4 could be left until later, or dropped altogether if you are really short of time;

The last column on the right contains additional advice about some of the activities.

Block 5 activities

Activity	Category				Comments
	1	2	3	4	
1.1			✓		Revises earlier material
1.2			✓		Revises earlier material
2.1				✓	Emphasizes a point made in the text, and could be dropped if you take the idea on trust!
2.2	✓				Needs to be studied here
2.3	✓				Needs to be studied here
4.1			✓		Revises earlier material
4.2				✓	A planning aid only
5.1			✓		A useful synthesis of Section 5
6.1				✓	Useful for reflection
9.1		✓			Provides a break from the text!
11.1		✓			Important, but can be used to a minimal extent if necessary
11.2			✓		A useful synthesis of Section 11
12.1				✓	Useful for reflection and tutorial discussion
12.2				✓	Useful for reflection and tutorial discussion

From 'The Times Higher Education Supplement', 30 June 1995, pp. 16–17.

Martin Rees describes how cosmologists aim to set our solar system in a grand evolutionary scheme by describing a cosmic history probably beginning with a 'big bang'.

Universal picture

Whilst this planet has been cycling on according to the fixed law of gravity, from so simple a beginning forms most wonderful ... have been and are being evolved." These are the concluding words of Charles Darwin's *On the Origin of Species*. Cosmologists aim to go back before Darwin's "simple beginning" to set our solar system in a grand evolutionary scheme stretching back to the formation of the Milky Way galaxy — right back to a so-called "big bang" that set our entire observable universe expanding, and imprinted the physical laws that govern it.

About 4.5 billion years ago our sun, a typical star, condensed from an interstellar cloud, and contracted until the centre became hot enough to ignite fusion of hydrogen into helium. This process will keep it shining until, after another 5 billion years, the hydrogen runs out. The Sun will then flare up, becoming large enough to engulf the inner planets and to vapourise all life on earth. After this "red giant" phase the inner regions will contract into a white dwarf — a dense star no larger than the earth, though nearly a million times more massive.

We are quite confident about these calculations because the relevant physics has been well studied in the lab — atomic and nuclear physics, Newtonian gravity and so forth. Astrophysicists can just as easily compute the life cycles of stars with half the Sun's mass, twice, four times and so on. Heavier stars burn brighter and trace out their life cycle more quickly.

Stars live so long compared with astronomers that we are granted just a single "snapshot" of each one's

life. But we can test our theories by looking at the whole population of stars. Trees can live for hundreds of years. But even if you had never seen a tree before, it would take no more than an afternoon in a forest to deduce their life cycle: from looking at saplings, fully grown specimens and some that had died.

In, for instance, the Orion Nebula, new stars are even now condensing within glowing gas clouds. The best "test beds" for checking such calculations are globular clusters — swarms of a million different stars, held together by their mutual gravity, which all formed at the same time,

But not everything in the cosmos happens slowly; sometimes stars explode catastrophically as supernovae. The closest supernova of the 20th century occurred in 1987. Its sudden brightening and gradual fading have been followed not only by optical astronomers but by those using other techniques — radio, X-ray and gamma-ray telescopes — that have opened new "windows" on the universe.

In about 1,000 years, it will look like the Crab Nebula, the relic of a supernova witnessed and recorded by Chinese astronomers in 1054 AD. Now, nearly 1,000 years later, we see the expanding debris from the explosion. The Crab nebula will remain visible, gradually expanding and fading, for a few thousand years; it will then become so diffuse that it merges with the very dilute gas and dust that pervade interstellar space.

Supernovae fascinate astronomers. But why should anyone else care about explosions thousands of light years away? Because, were it not for supernovae, there would be no planets, still less any complex evolution on them.

Of the 92 chemical elements that occur naturally, some are vastly more common than others. For every 10 atoms of carbon, you would find, on average, 20 of oxygen, and about five each of nitrogen and iron. But gold is a million times rarer than oxygen and others — platinum and mercury, for instance — are rarer still.

Why are carbon and oxygen common, but gold and uranium so rare? This everyday question is not unanswerable — but the answer involves ancient stars that exploded in our Milky Way more than five billion years ago, before our solar system formed.

Stars much heavier than the sun evolve in a more complicated and dramatic way. After they have used up their central hydrogen (and turned into helium) gravity squeezes them further. Their centres get still hotter, until helium atoms can themselves stick together to make the nuclei of heavier atoms — carbon (six protons), oxygen (eight protons) and iron (26 protons). A kind of "onion skin" structure develops: where the hotter inner layers have been transmuted further up the periodic table.

When their fuel has all been consumed (when their hot centres are transmuted into iron) big stars face a crisis. A catastrophic infall squeezes their centres to the density of an atomic nucleus, triggering an explosion that blows off the outer layers. This explosion manifests itself as a supernova of the kind that created the Crab Nebula.

The debris contains the outcome of all the nuclear alchemy that kept the star shining over its entire lifetime — a lot of oxygen and carbon, plus traces of many other elements. The calculated "mix" is gratifyingly close

to the proportions now observed in our Solar System.

The Milky Way, our home galaxy, resembles a vast ecosystem. Pristine hydrogen is transmuted, inside stars, into the basic building blocks of life — carbon, oxygen, iron and the rest. Some of this material returns to interstellar space, thereafter to be recycled into new generations of stars.

A carbon atom, forged in an early supernovae, might wander for hundreds of millions of years in interstellar space. It might then have found itself in a dense interstellar cloud, which collapsed under its own gravity to form stars. It might have joined one of the less massive stars, each surrounded by a spinning gaseous disc that condenses into a retinue of planets. One such star could have been our Sun. The same carbon atom may have found itself in the newly forming Earth, perhaps eventually in a human cell.

Each atom has a pedigree extending back far earlier than our solar system's birth. We are literally the ashes of long-dead stars.

The Big Bang

How did our galaxy itself emerge? And where did the basic hydrogen come from? Did everything really start with a so-called "big bang"?

The idea goes back to Belgian Catholic priest Georges Lemaître in 1930 but the clinching evidence for the theory came in 1965, when Penzias and Wilson found excess microwave noise, coming equally from all directions and with no obvious source, in their antenna at the Bell Telephone Laboratory. This has momentous implications — intergalactic space is not completely cold — it's about 3 degrees above absolute zero. That may not seem much, but there are about a billion quanta of radiation — photons — for every atom in the universe.

This "cosmic background" causes some 1 per cent of the background "fuzz" on a television set. It is an "afterglow" of a pregalactic era when the entire universe was hot and dense and opaque. After expanding for about half a million years the temperature fell below 3,000K; the primordial radiation then shifted into the infrared. The universe literally entered a dark age, which persisted until the first stars in the first galaxies, and maybe also the first

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quasars, formed and lit space up again. The expansion cooled and diluted the radiation, and stretched its wavelength. But it would still be around — it fills the universe and has nowhere else to go.

But we have got firm grounds for believing that temperature was once billions of degrees, not just thousands — hot enough for nuclear reactions. The rapid expansion did not allow time for everything to be processed into iron, as in hot stars. However, about 25 per cent would have turned into helium. The rest would still be hydrogen apart from traces of deuterium and lithium.

What is remarkable is that the proportion of helium in old stars and nebulae — now pinned down with 1 per cent accuracy — turns out to be just about what is calculated. As a bonus, so are the proportions of lithium and deuterium too.

Over the past few years, the case for a "big bang" has had several boosts — the COBE (Cosmic Background Explorer) satellite showed that the background radiation had the expected spectrum, to a precision of a part in 10,000; and there have been better measurements of cosmic helium and deuterium. Moreover, there are several discoveries that might have been made, which would have invalidated the hypothesis, and which have not been made — the big bang has lived dangerously for 25 years and survived.

The theory boasts fervent believers. The great Soviet cosmologist Zeldovich once claimed that the big bang was "as certain as that the Earth goes round the Sun" (even though he must have known his compatriot Landau's dictum that cosmologists are "often in error but never in doubt").

I would bet at least 90 per cent on the general concept that we can extrapolate back to when the universe was a second old.

The Future

Cosmic timespans extend at least as far into the future as into the past. Suppose America had existed for ever, and you were walking across it, starting on the east coast when the Earth formed, and ending up in California ten billion years later, when the Sun was about to die. To make this journey, you would have to take one step every 2,000 years. All

recorded history would be three or four steps, just before the halfway stage — somewhere in Kansas perhaps. In this perspective, we are still near Darwin's "simple beginning" of the evolutionary process. The progression towards diversity has much further to go. Even if life is now unique to the Earth, there is time for it to spread from here through the entire galaxy, and even beyond.

In about five million years the Sun will die; and the Earth with it. At about the same time (give or take a billion years) the Andromeda Galaxy, already falling towards us, will crash into our own Milky Way, merging to form a single amorphous elliptical galaxy.

But will the universe expand for ever, attaining some asymptotic "heat death"? Or will it, after an immense time, recollapse to the big crunch? The ultra-long-range forecast depends on how much the cosmic expansion is decelerating. The deceleration comes about because everything in the universe exerts a gravitational pull on everything else. It is straightforward to calculate that the expansion will eventually go into reverse if the average cosmic density exceeds about three atoms per cubic metre. But space seems even emptier than that: if the atoms in all the stars and gas in all the galaxies were dispersed uniformly, they would fall short of this "critical" density by a factor of at least 50.

At first sight this seems to imply perpetual expansion, by a wide margin. But the case is not so straightforward, because there seems to be at least ten times as much material in "dark" form as we see directly.

What could this dark matter be? Maybe it is faint stars whose centres are not squeezed hot enough to ignite their nuclear fuel; or black holes — remnants of big stars that were bright when the galaxy was young but have now died.

But there are other options. The hot early universe may have contained not just atoms and radiation, but other particles as well. In particular, there should be huge numbers of neutrinos — about a billion for every atom in the universe. So even a very tiny individual mass would make the cumulative gravitational effects of neutrinos important. But do neutrinos

have any mass at all? Recent experiments at Los Alamos suggest that they do. But these have so far been announced in the *New York Times*, and not yet in a proper scientific journal, so we would be prudent to suspend judgement. If the claimed mass is right, neutrinos contribute more gravitating stuff than all the stars and gas in the universe.

At least we know neutrinos exist. But particle theorists have a long shopping list of particles that might exist, and (if so) could have survived from the early phases of the big bang. If such particles pervade our galaxy, there would be 100,000 of them in every cubic meter, most passing straight through the Earth without interacting. But their cross-section for colliding with ordinary atoms, though tiny, is not quite zero, and sensitive experiments are being set up to detect the rare events when this happens.

The equipment must be placed deep underground, to reduce other types of background signal. A group in the United Kingdom is building such an experiment down a mine in Yorkshire. It is a difficult experiment, but a positive result would not only reveal what 90 per cent of the universe is made of, but also discover new types of particle that could never be detected in other ways.

We should not be surprised that there is dark matter. There is no reason why everything in the universe should shine. The challenge is to decide among many candidates. Dark matter's dominance may demote our cosmic status still further. Copernicus dethroned the Earth from a central position. Hubble showed that the Sun was not in a special place. But now particle chauvinism may have to go. We ourselves, and all the stars and galaxies would then be trace constituents of a universe whose large-scale structure is controlled by the gravity of dark matter of a quite different kind — we see, as it were, just the white foam on the wave crests, not the massive waves themselves.

People often wonder how the universe can have started off in thermal equilibrium — a hot, dense fireball — and ended up manifestly far from equilibrium. Temperatures now range from blazing surfaces of stars to the night sky only three degrees above absolute zero.

Although this seems contrary to thermodynamic intuitions that temperatures tend to equilibrate as things evolve, it is actually a natural outcome of cosmic expansion, and the workings of gravity.

Gravity has the peculiar tendency to drive things further from equilibrium. When gravitating systems lose energy they get hotter. A star that loses energy and deflates ends up with a hotter centre than before. To establish a new and more compact equilibrium where pressure can balance a (now stronger) gravitational force, the central temperature must rise.

And gravity does something else. It renders the expanding universe unstable to the growth of structure, in the sense that even very slight initial irregularities would evolve into conspicuous density contrasts. Theorists are now carrying out increasingly elaborate computer simulations of how this happened.

If one had to summarise what has been happening since the big bang the best answer might be: "Ever since the beginning, gravity's 'antithermodynamic' effects have been amplifying inhomogeneities, and creating progressively steeper temperature gradients — a prerequisite for emergence of the complexity that lies around us ten billion years later, and of which we're part."

The Ultra-early Universe

Cosmic history can be divided into three parts: part one is the first millisecond, a brief but eventful era spanning 40 decades of logarithmic time. This is the intellectual habitat of the high-energy theorist and the quantum cosmologist.

The second stage runs from a millisecond to about a million years. It is an era where cautious empiricists like myself feel more at home. The densities are far below nuclear density, but everything is still expanding in an almost homogeneous fashion. The relevant physics is firmly based on laboratory tests, and theory is corroborated by good quantitative evidence — the cosmic helium abundance, the background radiation and so on. This stage, though it lies in the remote past, is the easiest to understand.

The tractability lasts only so long as the universe remains amorphous and structureless. When the first

gravitationally bound structures condense out — when the first stars, galaxies and quasars have formed and lit up — the era studied by traditional astronomers begins. We then witness complex manifestations of well-known basic laws. Gravity, gas dynamics and feedback effects from early stars, combine to initiate the complexities we see around us and are part of.

But we then realise that the few basic numbers that determine how the universe has evolved are all legacies of the uncertain physics of the first phase. Even the physical laws themselves may have been imprinted in the ultra-early universe. (This is speculative territory.) First, what about the initial expansion rate? This has to be very precisely tuned. The two eschatologies — perpetual expansion or recollapse to a "crunch" — seem very different. But our universe is still expanding after 10 billion years. Had it recollapsed sooner, there would not have been time for stars to evolve — indeed, if it had collapsed after less than a million years it would have remained opaque, precluding any thermodynamic disequilibrium. On the other hand, the expansion cannot be too much faster than the critical rate. Otherwise gravity would have been overwhelmed by kinetic energy and the clouds that developed into galaxies would have been unable to condense out.

In Newtonian terms the initial potential and kinetic energies were very closely matched. How did this come about? And why does the universe have the large-scale uniformity which is a prerequisite for progress in cosmology?

The answer may lie in something remarkable that happened during the first 10^{-36} seconds. Ever since that time, the cosmic expansion has been decelerating, because of the gravitational pull that each part of the universe exerts on everything else. But theoretical physicists have come up with serious (though still, of course, tentative) reasons why, at the colossal densities before that time, a new kind of "cosmical repulsion" might come into play and overwhelm "ordinary" gravity. The expansion of the ultra-early universe would then have been inflated, homogenised, and established the "fine-tuned" balance between gravitational and kinetic

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energy when it was only 10^{-36}
seconds old.

This generic idea that the universe went through a so-called inflationary phase is compellingly attractive. The fluctuations from which clusters and superclusters form, and the even vaster ones whose imprint on the background radiation spreads right across the sky, may be the outcome of microscopic quantum phenomena from an ultra-ancient epoch when the universe was squeezed smaller than a golfball. (The two foundations of 20th-century physics are Einstein's theory of gravity on the one hand, and the quantum uncertainty

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principle on the other. But there is no overlap between these two concepts. Gravity is so weak that it is negligible on the scale of single molecules, where quantum effects are crucial. Conversely, gravitating systems like planets are so large that quantum effects can be ignored in studying how they move. But right back at the beginning of the universe, the densities could have been so high that quantum effects were important for the whole universe.)

We do not, of course, know the physics that prevailed at this ultra-early time. But there is a real prospect of discovering something

about it. Specific models of how the inflation is driven make distinctive predictions about things we can observe — large-scale clustering, and small non-uniformities in the background radiation over the sky. We shall soon be confronting these speculations about the ultra-early universe with real empirical tests.

Martin Rees is a Royal Society professor, Cambridge University, and the Astronomer Royal. This is an edited extract from his Darwin lecture.